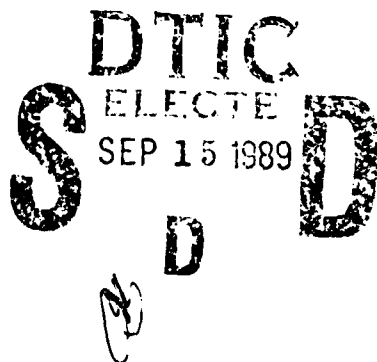# Naval Research Laboratory

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Scaling of an 85 GHz Gyrotron
to Operate at 94 GHz

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Vienna, VA

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19 ABSTRACT (Continue on reverse if necessary and identify by block number)

This paper describes how a 94 GHz, 70 kV gyrotron operating in the TE_{13} mode was designed and built. The novel feature of the design is that it was based to a large degree on a previously built gyrotron that operated at a lower frequency. The highest efficiency achieved was 32% at 4A which agrees well with theoretical predictions. The highest power measured was 135 kW at 12 A.

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A-1

SCALING OF AN 85 GHZ GYROTRON
TO OPERATE AT 94 GHZ

I. Introduction

The gyrotron is an effective high average power cyclotron maser whose principle of operation is to match the electron cyclotron frequency to the resonant frequency of a desired cavity mode. The ability of gyrotron cavities to operate in modes with large transverse eigennumbers is of considerable interest due to the increase in cavity cross-section and power rating compared with a fundamental mode cavity.

TE_{1n} modes are attractive candidates for high power, short wavelength operation. Studies of TE_{13} mode gyrotrons have been carried out using short electron pulses, on the order of 50 nanoseconds (Ginzberg et al 1978, Bratman et al 1981, Voronkov et al 1982, Gold et al 1988). Recently, this time has been extended to microsecond pulses (Rhinewine and Read 1986).

In this paper we describe a 94 GHz, 70 kV, TE_{13} mode gyrotron designed to operate in the microsecond range. Relatively stable operation was achieved without the necessity of slotting the cavity walls. Power was observed up to 135 kW at high current (12 A). Efficiency was 32% at low current (4 A), in agreement with the theoretically predicted value. Lower efficiencies at higher currents are measured, similar to results obtained by both Varian (K. Felch, private discussion) and M.I.T. (Kreischer et al, 1988) with their high power gyrotrons. It is speculated that this anomaly may be due to some type of beam instability.

II. Design Considerations

The design of the 94 GHz TE_{13} mode gyrotron was based on a successful predecessor, the 85 GHz TE_{13} mode gyrotron described elsewhere (Rhinewine and Read 1986).

The issues that had to be addressed were the following:

A. Would the old electron gun work at the higher value of magnetic
   field and r.f. frequency.

B. Would the electrons from this gun, operating at the new

1

parameters, propagate through the gyrotron without interception.

C. Would the dimensions used in the cavity design successfully in

the 85GHz TE$_{13}$ gyrotron scale to the higher frequency.

A. The magnetron injection gun we planned to use was originally designed for use with a TE$_{01}$ gyrotron operating at 35 GHz with a magnetic field compression ratio of 6.7 (Seftor 1979). To determine the increase in compression ratio for operation at 94 GHz, a code based on a paper by Baird and Lawson (1986) was used. The compression ratio was found to be 15 with the same mod anode voltage as for 35 GHz operation; i.e, 0.47 of the cathode voltage, which was 70 kV.

B. Running an electron trajectory code (Herrmannsfeidt 1979), it was found that increasing the magnetic field compression ratio from 6.7 to 15 would indeed allow the electrons to get through the narrower input section, smaller cavity, etc., without interception or mirroring.

C. Utilizing cavity and efficiency codes previously run for the 85 GHz gyrotron, it was found that a cavity whose linear dimensions were scaled down from the 85 GHz cavity, i.e., in the ratio of 85/94, should oscillate at 94 GHz, have a Q = 600, and an axial length of 6.8 free space wavelengths. Mode conversion was calculated as approximately 15% due to the output taper of the cavity. All these parameters were similar to those of the 85 GHz gyrotron. Figure 1 shows the normalized electric field profile, |F|, in the cavity region.The dashed line is the wall outline, including part of the drift region, the input taper, the cavity straight wall section and the double output taper.

Using a code developed by A.W. Fliflet, the performance characteristics of the gyrotron were calculated. Figure 2 is the calculated current versus magnetic field for various values of calculated output power (the lowest curve represents the lowest possible starting current, about 2 A at 3.7T). Figure 3 shows the calculated efficiency versus current for the range of magnetic fields in which the gyrotron was expected to operate, 3.57 - 3.78 Tesla. The theoretically predicted maximum efficiency is at 12 A. Figure 4 shows the calculated power versus current for the same magnetic fields. Not surprisingly, the high powers are at

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relatively high currents for the same magnetic fields.

III.   Experimental Set-Up

Figure 5 is a block diagram of the 94 GHz TE_{13} mode gyrotron. The same electron gun, cavity holder, collector and pump-out section that were used in the 85 GHz gyrotron were reused. Here the input section of the cavity holder had to be modified to accommodate the smaller copper scraper and Macor^{TM} absorber rings used in the drift section. The new cavity section, shown in Figure 6, has the same outer dimensions as its predecessor, so no further machining of the housing was required. In order to reuse the relatively expensive pump-out waveguide which has an uptaper to the window, a downtaper had to be machined to match the new BeO window now designed for minimum reflection at 94 GHz.

To characterize the gyrotron's output parameters (microwave frequency, power, mode, efficiency) as fully as possible, it was operated over the following parameter ranges:

            Voltage.....................50 - 75 kV

            Current.....................2 - 14 A

            Field........................3.6 - 3.8 T

            Pulse Duration...............2 microseconds (fixed)

            Pulse Repetition Frequency...1 - 30 pps

Frequency was measured using a standard wavemeter with a resolution of 200 MHz at 94 GHz. Average power was measured with a commercial laser calorimeter that has been modified for maximum absorption at 85 GHz and reflects about 10% of the incident power at 94 GHz. The calculated power measurements are not corrected for this loss, and so are a lower bound on the powers claimed. Attempts at mode identification were carried out with burn paper, liquid crystal and far field antenna pattern measurements. Efficiency was calculated from measured output average power corrected for the duty cycle and knowledge of the input voltage and collector current.

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IV. Experimental Results

As can be seen from the ensuing plots,(Figures 7 through 9), microwaves were obtained over a wide range of input voltages, currents and magnetic fields. Figure 7 is a plot of the theoretical starting current versus magnetic field, with the experimental data covering a wide range of collector currents and magnetic fields. Figures 8 and 9 are repeats of the theoretical curves in Figures 3 and 4 with the experimental data appropriately plotted. The shaded portions in these two last Figures delineate the magnetic field bounds within which most of the microwaves measured were seen (i.e. 3.59 T $\leq$ B $\leq$ 3.75 T was where the gyrotron oscillated reliably). Figure 10 is a plot of the data showing measured frequency versus calculated electron cyclotron frequency.

Burn patterns and liquid crystal patterns showed significant power on axis. Far field antenna measurements were made with a rectangular horn connected to a crystal detector; the horn was oriented first horizontally, then vertically. Plots of the resultant curves are shown: Figure 11 is the theoretical curve for the far field antenna pattern when the horn is oriented so as to pick up waves with a vertical B field and Figure 12 shows what was actually measured. Similarly, Figures 13 and 14 show the theoretical and experimental curves when the horn is in the horizontal orientation.

V. Discussion of Results

The gyrotron operated in the 93.5 - 94.5 GHz frequency range (Figure 10), which centers around the design frequency of 94 GHz. Most stable operation was obtained in the 94.1 - 94.5 GHz range. All the higher microwave output powers (greater than 100kW) were in this frequency range.

The detuning between the electron cyclotron frequency and the measured frequency for each data point in Figure 10 is characteristic of gyrotron behavior. The average detuning goes from approximately 5% at the lower frequencies to 2% at the higher frequencies, which represents a typical range for this type of gyrotron. The theoretical plot of efficiency versus

current (Figure 3) shows highest efficiencies at 9 - 10 A, but the best measured efficiencies were in the 4 - 6 A range, with the highest, 32%, at only 4 A (Figure 8). It has been speculated that this discrepancy between theoretical and experimental efficiency at higher currents may be due to beam instability. As is evident from the plots in Figures 12 and 14, we did not achieve a pure TE_{13} mode; the radiation pattern is very skewed, which may be attributed to either a bend in the collector that was known to exist, or the additional tapers to the window, or both. The lack of sharply defined minima (except the one) might imply that there is a mixture of TE_{13} and TE_{12} modes (and probably others). Calculations with a code written by J. Levine indicate that more than 50% of the mode conversion is into the TE_{12} mode. The mode map in Figure 15 shows that there are no other TE_{1n} modes close enough in frequency to emanate from the cavity, so any TE_{12} mode cortent would be due to mode conversion in the tapers, window, etc. The only other modes near enough in frequency, the TE_{32} and TE_{71}, were not observed, as expected, since their start currents are higher than that of the TE_{13} mode.

VI. Summary

A gyrotron has been designed, built and tested to operate in the TE_{13} mode at 94 GHz. Stable frequency of operation was in the 94.1 -94.5 GHz range, which is close to the design frequency. Highest power measured was 135 kW at 12 A and an efficiency of 16%; and highest efficiency was 32% at 4 A at a calculated power of 85 kW. The gyrotron was operated in a pulsed mode at a repetition frequency of 30 pps with pulse width of 2 microseconds. Although the power on axis is indicative of TE_{1n} modes, it is clear that operation in a pure TE_{13} mode was not achieved; rather, a mixture of TE_{13} and TE_{12} modes were present at the output, probably due to mode conversion after the cavity.

The present gyrotron was built as a proof of the principle that scaling from 85 GHz to 94 GHz is possible with simple scaling of cavity dimensions. However, there were several known deficiencies that were not addressed in the design of the 85 GHz gyrotron, and consequently were continuing problems in the 94 GHz gyrotron:

A. Soft seals (Viton O-rings) had to be used, both to effect a current break between the cavity section and the collector, and for the ultra-Torr^{TM} fitting used at the window. This eliminates the possibility of a proper high temperature bake-out, and therefore operation at higher average power (i.e. higher rep-rate) causes the gyrotron to heat up, become gassy and arc.

B. The relatively soft OFHC copper collector is easily deformed and makes good alignment in the bore of the magnet virtually impossible.

Both of these issues are being addressed in an ongoing redesign: No Viton O-rings will be used (a non-trivial design problem), and a stainless steel reinforced copper collector should alleviate the second problem. An alternative solution would be to fabricate the collector from dispersion hardened copper, Glidcop^{TM} (K. Felch, private discussion).

Acknowledgements

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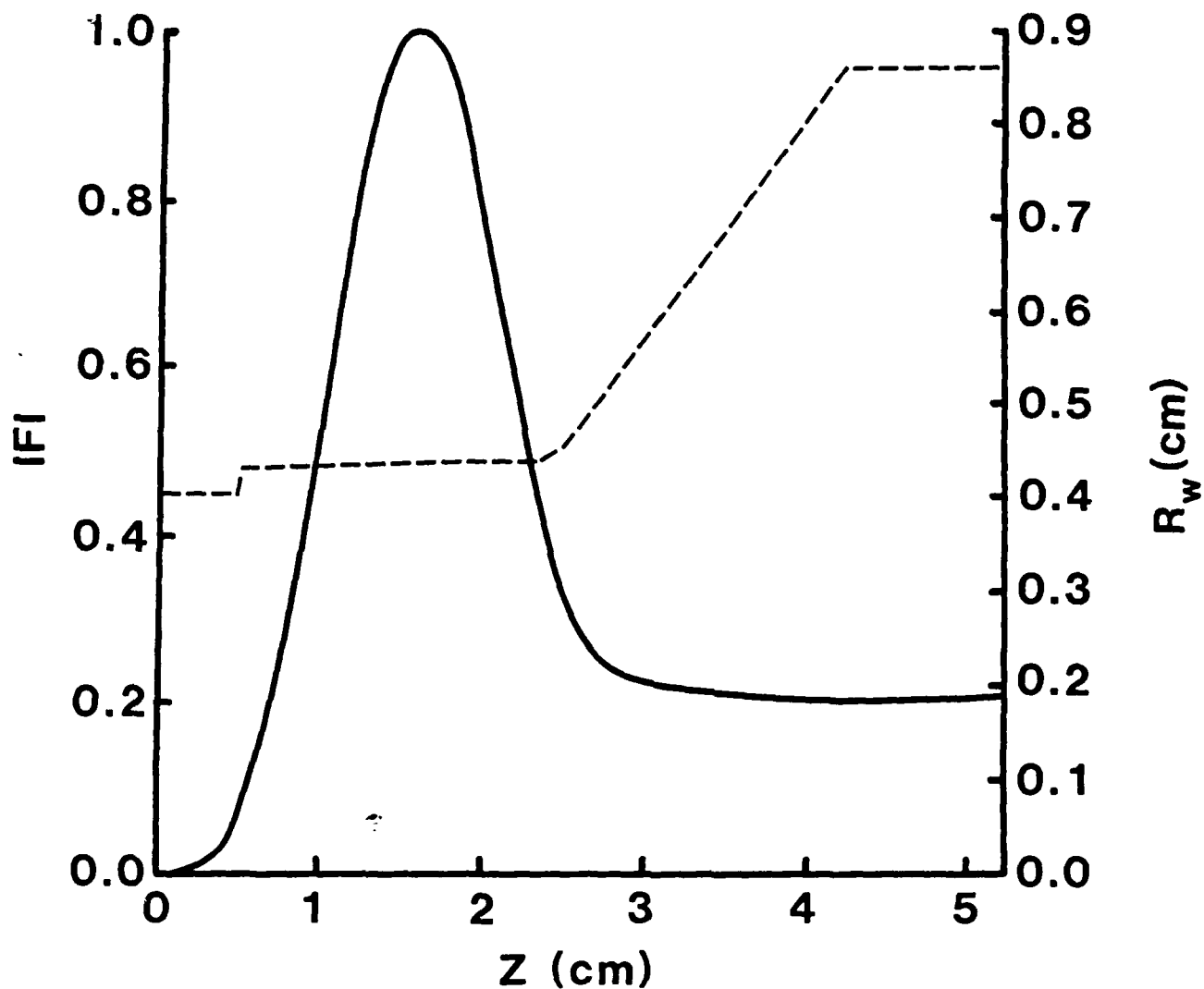
Figure 1: Profile of the calculated electric field (normalized) in the cavity region. The right side, labeled Rw, refers to the actual cavity dimensions outlined by the dashed line. Z is in the axial direction at the center of the cavity.
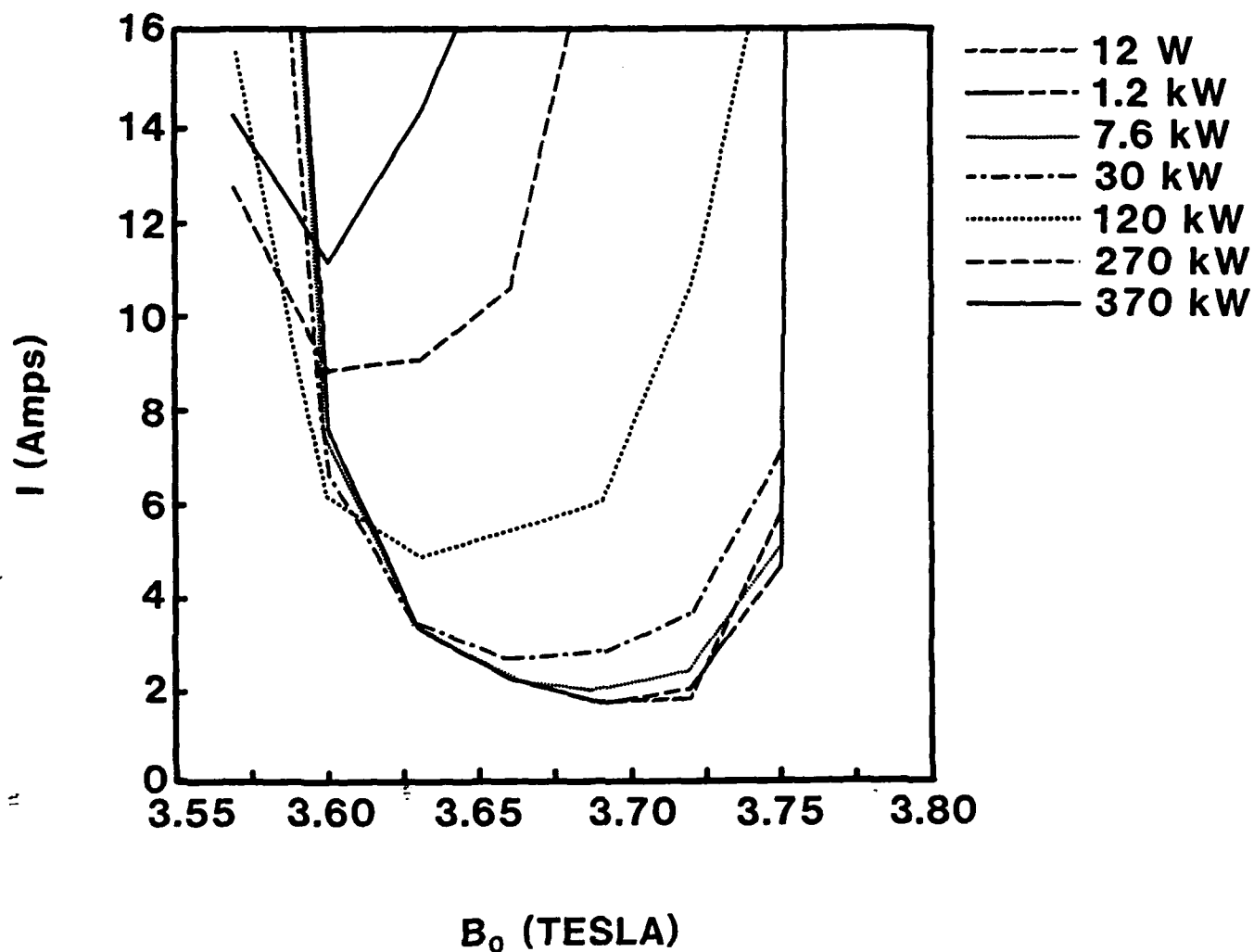
Figure 2: Collector current versus magnetic field for various values of output power. The lowest curve, calculated at extremely low power, represents the lowest possible start current - about 2 A at 3.7 T.

TE$_{1,3}$ ROTATING MODE

94 GHz GYROTRON OSCILLATOR
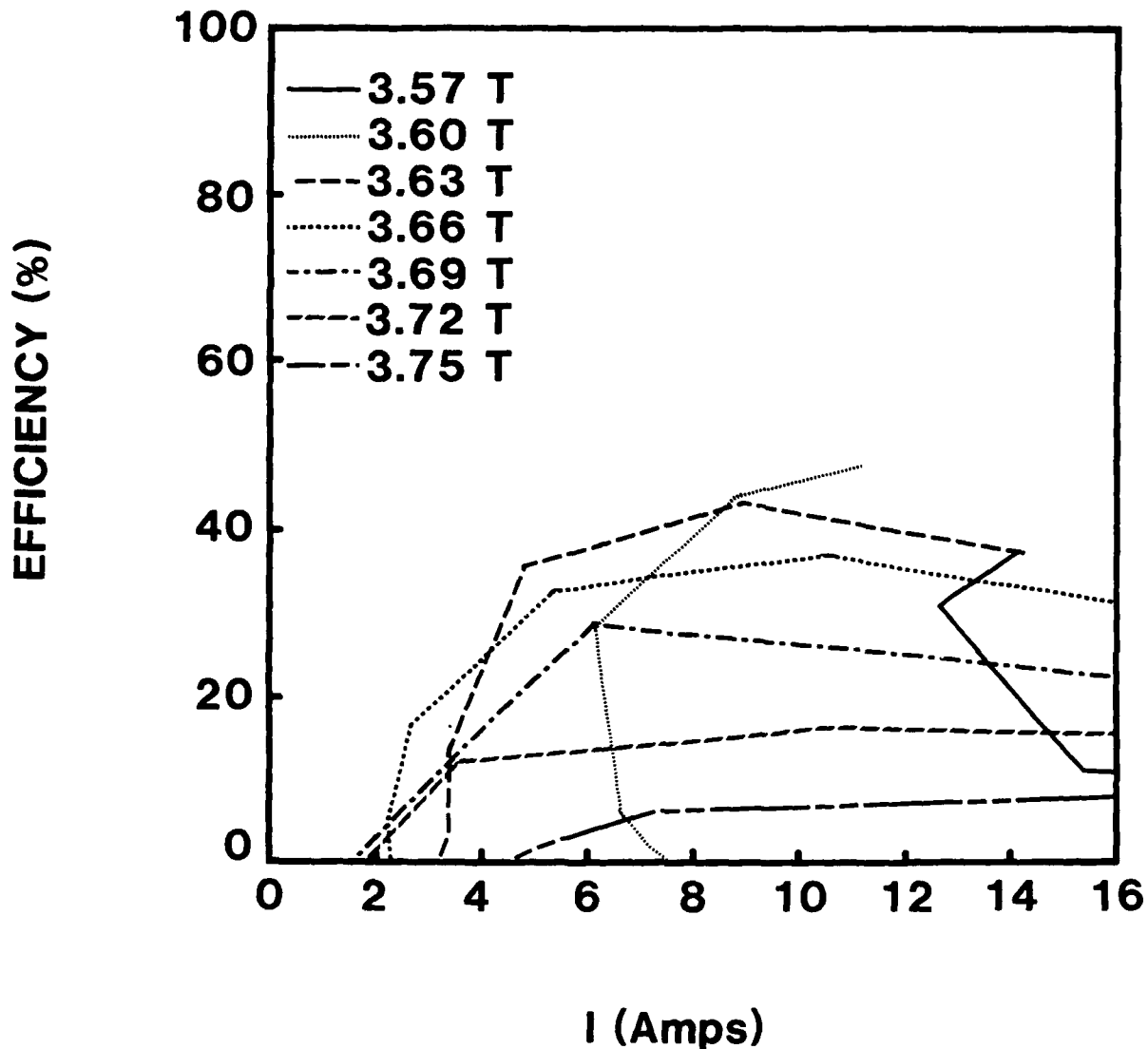
Figure 3: Efficiency versus collector current for various values of magnetic field. The highest theoretical efficiency (over 40%) should occur above 10 A.
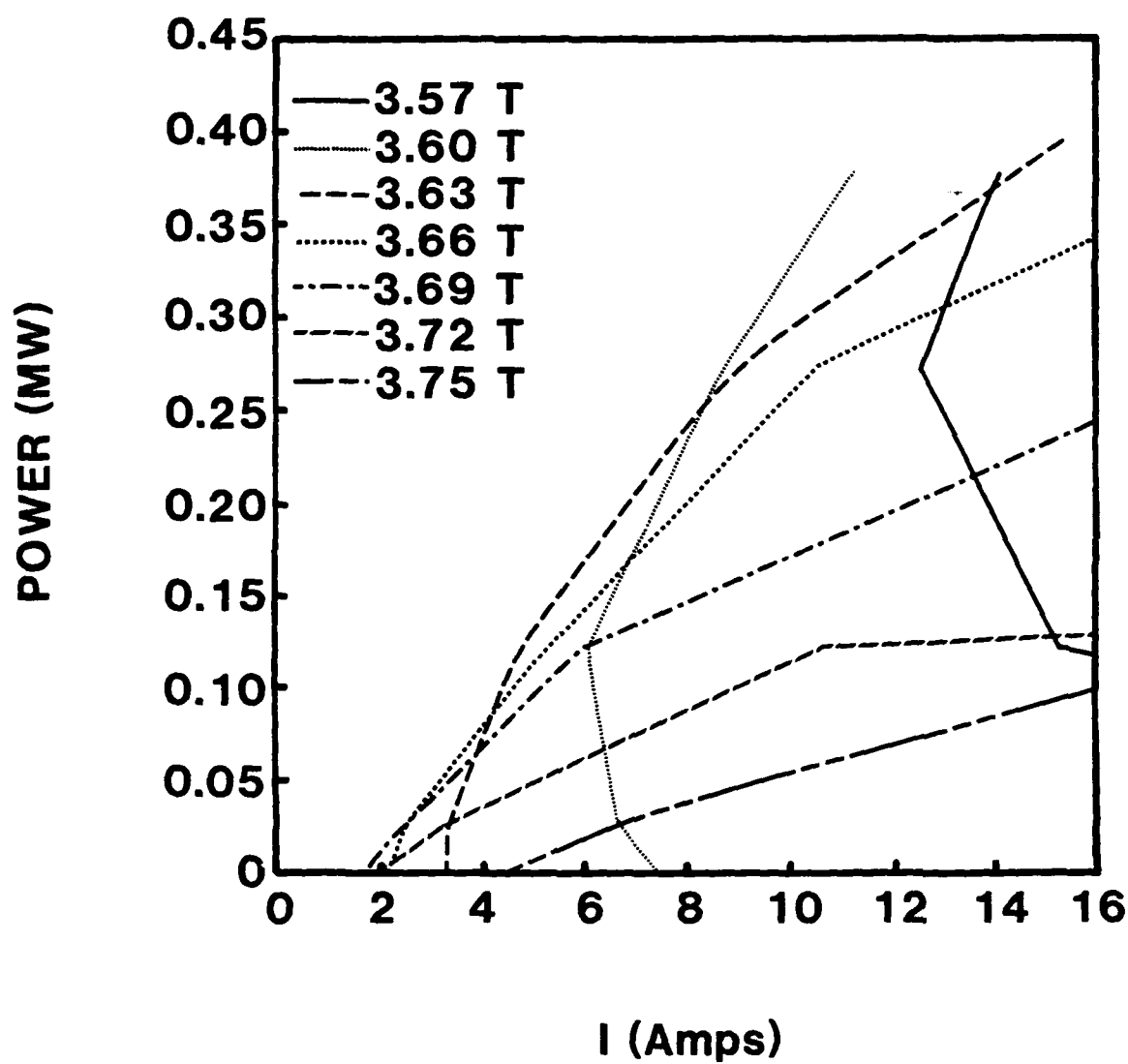
Figure 4: Output power versus collector current for various values of magnetic field. The powers scale roughly with current.

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94 GHz, TE$_{1,3}$ GYROTRON
(NOT DRAWN TO SCALE)

ELECTRON
GUN   COLLECTOR

CAVITY
SECTION   OUTPUT
WINDOW

PUMP-OUT
SECTION
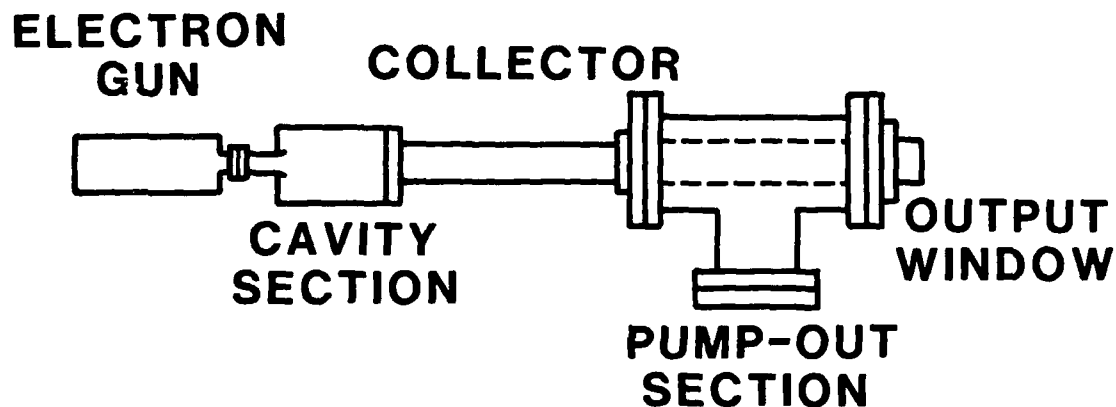
VOLTAGE = 70 KV

CURRENT = 10 Amp

α = 1.5

γ = 1.137

Figure 5:   Block diagram (not to scale) of the 94 GHz
gyrotron.

CUT-OFF REGION

INPUT TAPER

.870 cm

DOUBLE-TAPER OUTPUT
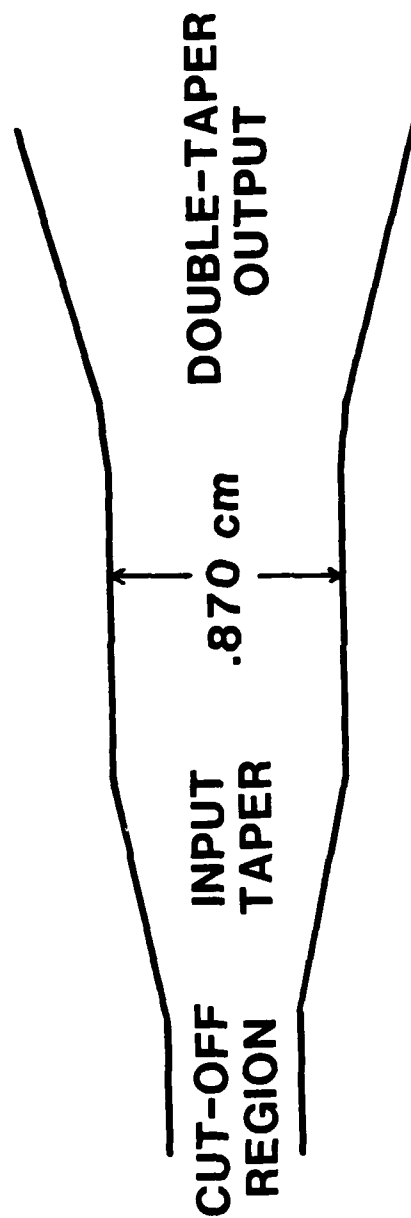
$f = 94.0$ GHz ($TE_{1,3}$)

$Q = 600$

$L/\lambda = 6.8$

MODE CONVERSION $< 15\%$

Figure 6: Cavity - not drawn to scale.

START CURRENT
94 GHz GYROTRON OSCILLATOR
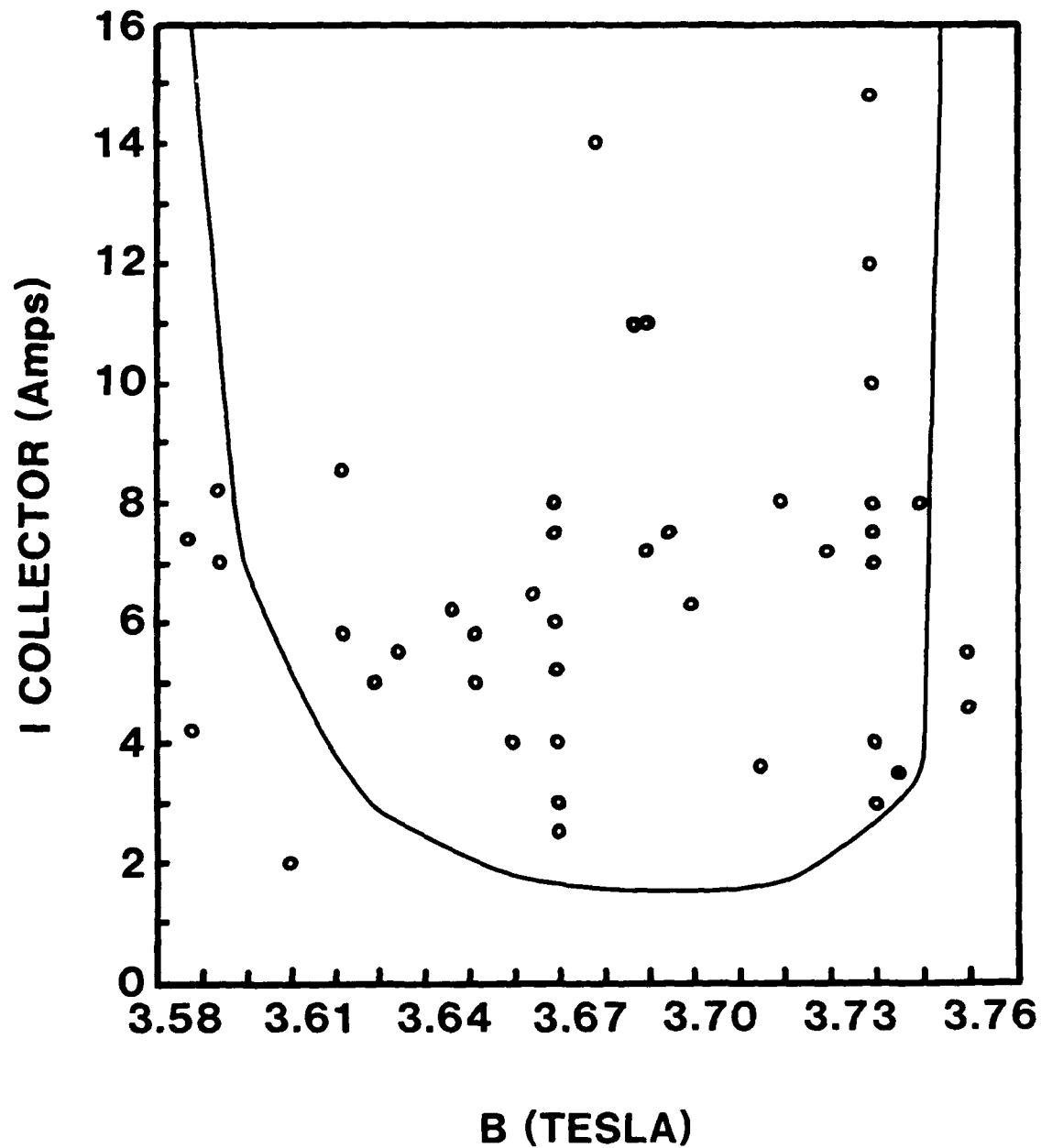
Figure 7: Microwaves measured at various collector currents and magnetic field. The solid line is the start current for the TE_{13} mode.

TE$_{1,3}$ ROTATING MODE

94 GHz GYROTRON OSCILLATOR
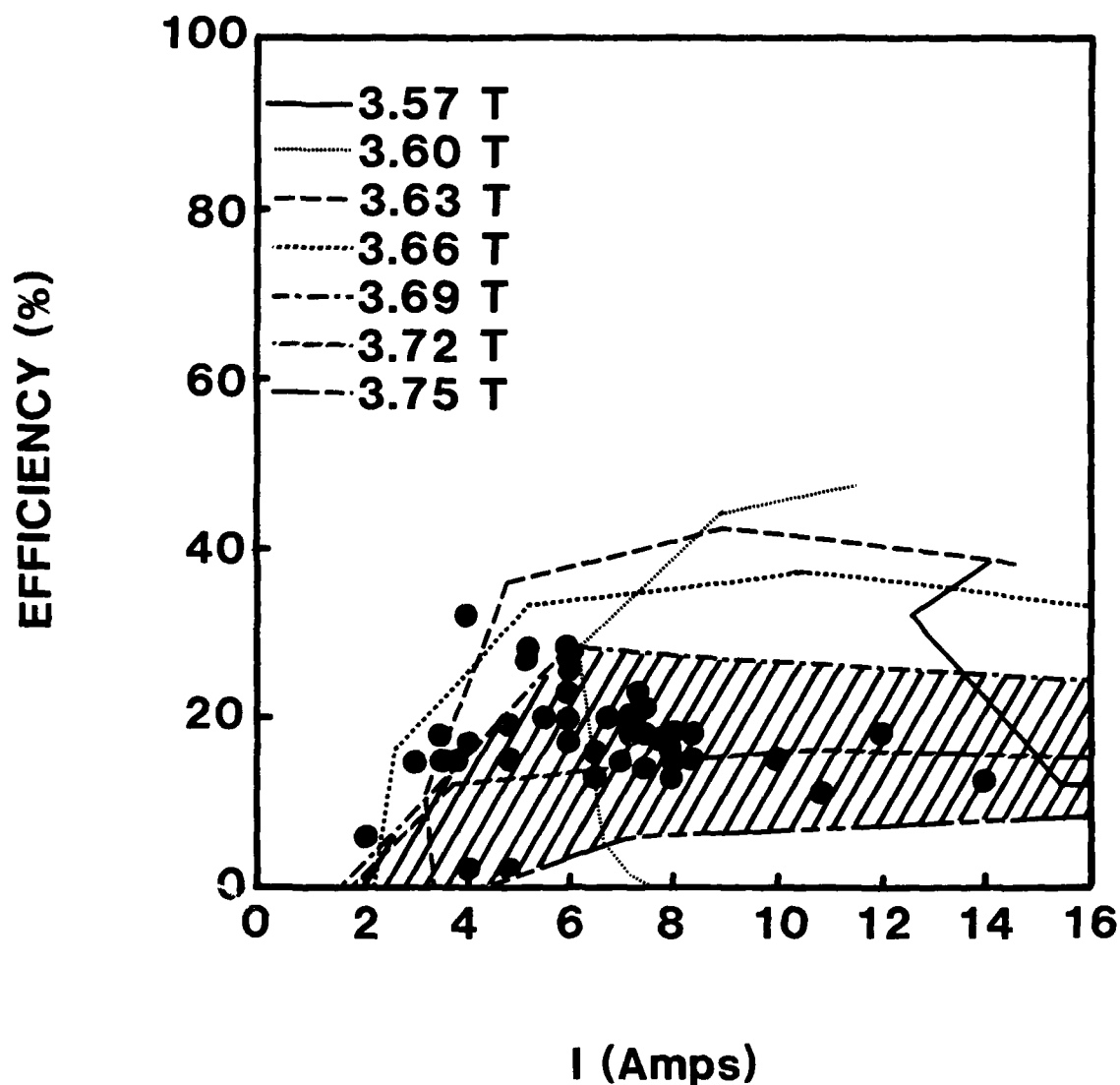
Figure 8: Efficiency versus collector current for the measured microwaves. The shaded region represents the magnetic field range within which most of the data points shown were measured.

TE$_{1,3}$ ROTATING MODE
94 GHz GYROTRON OSCILLATOR
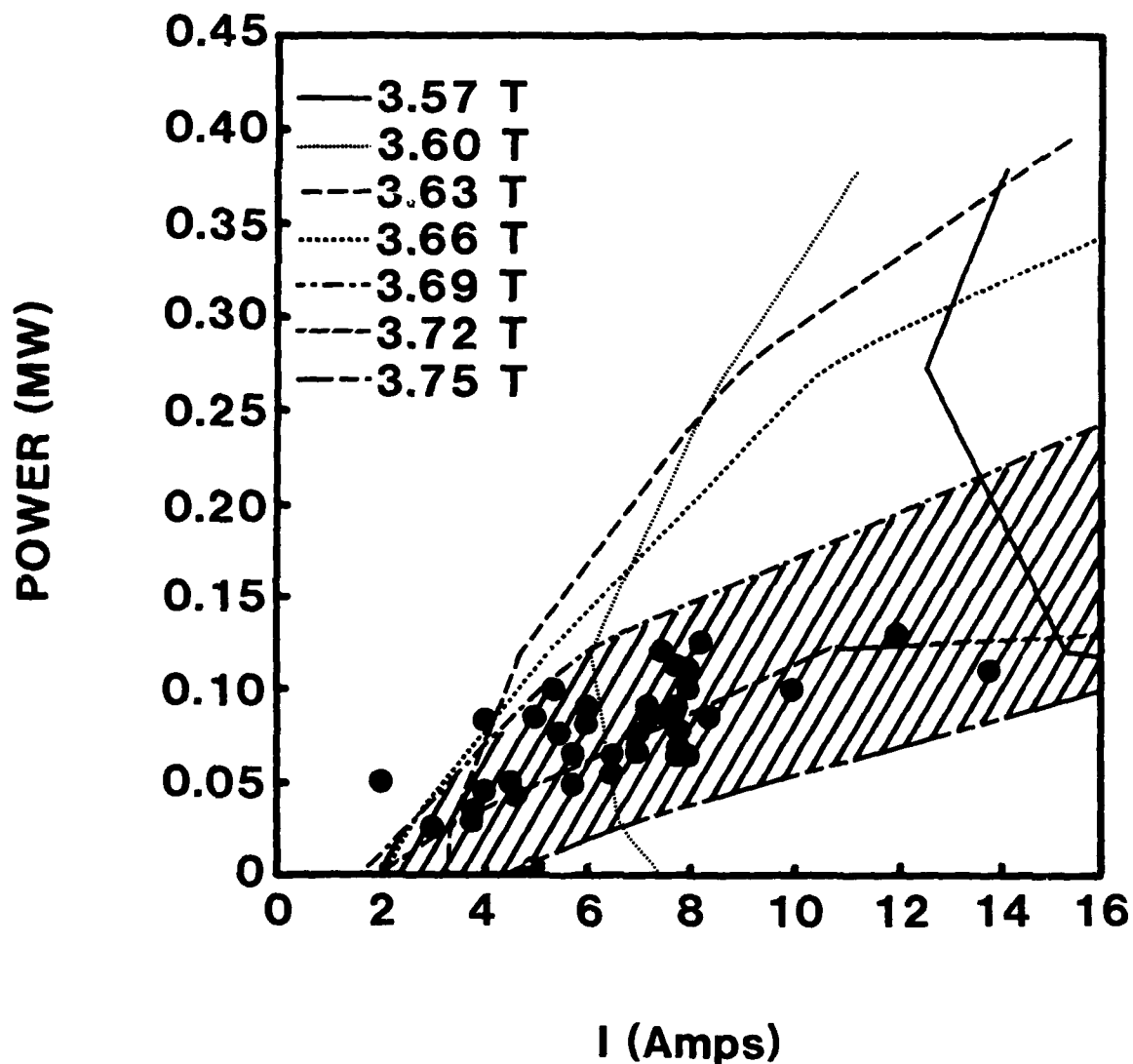
Figure 9: Power versus collector current for the measured microwaves. The shaded region represents the magnetic field range within which most of the data points shown were measured.
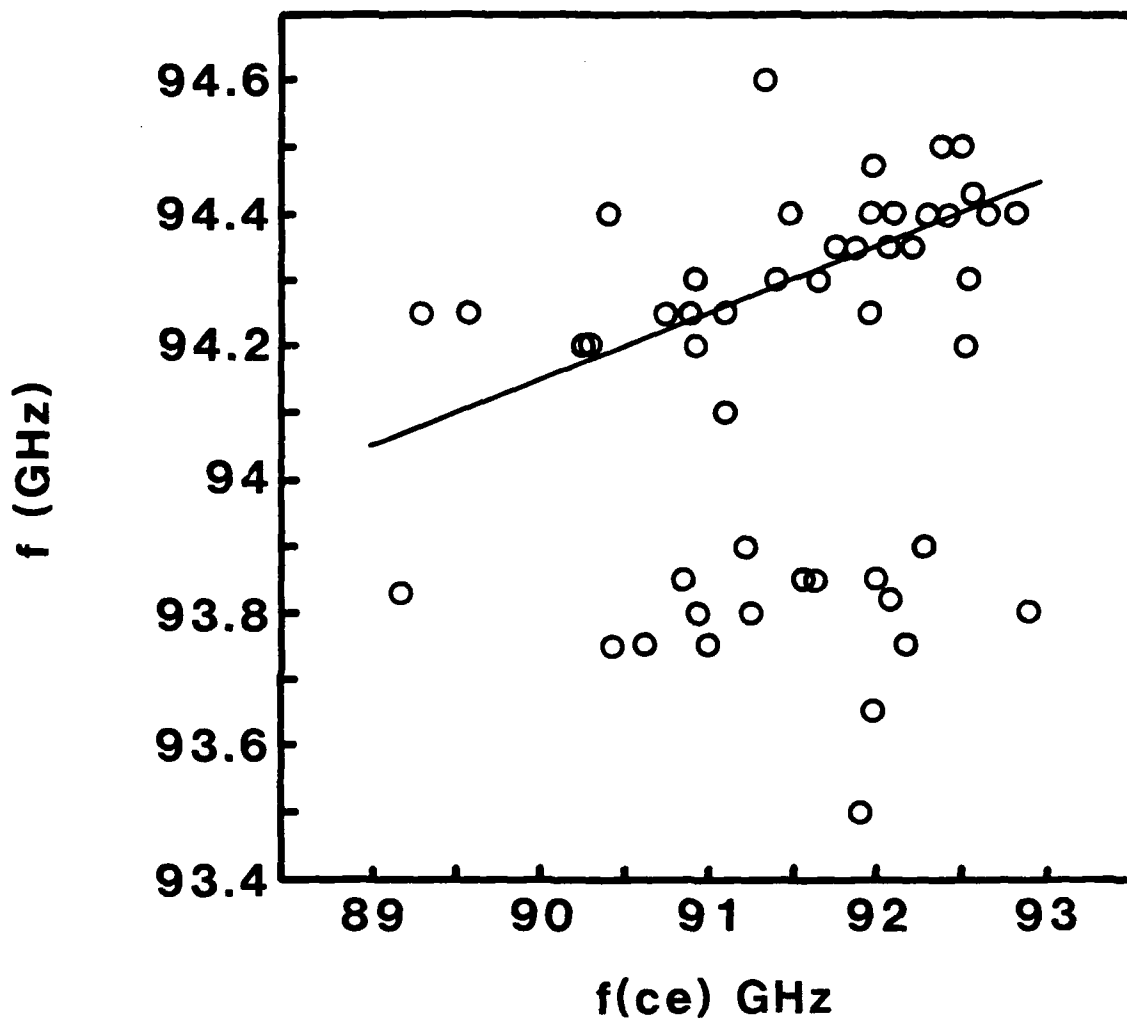
Figure 10:   Measured microwave frequency versus the
               corresponding calculated electron cyclotron
               frequency for each data point. The straight
               line represents the average detuning as a
               function of frequency: the low end is about
               5%, the high end about 2%.

THEORY – E PLANE

$TE_{1,n}$
$\underline{E} \parallel$ TO SWING

THETA

FIELD MAGNITUDE
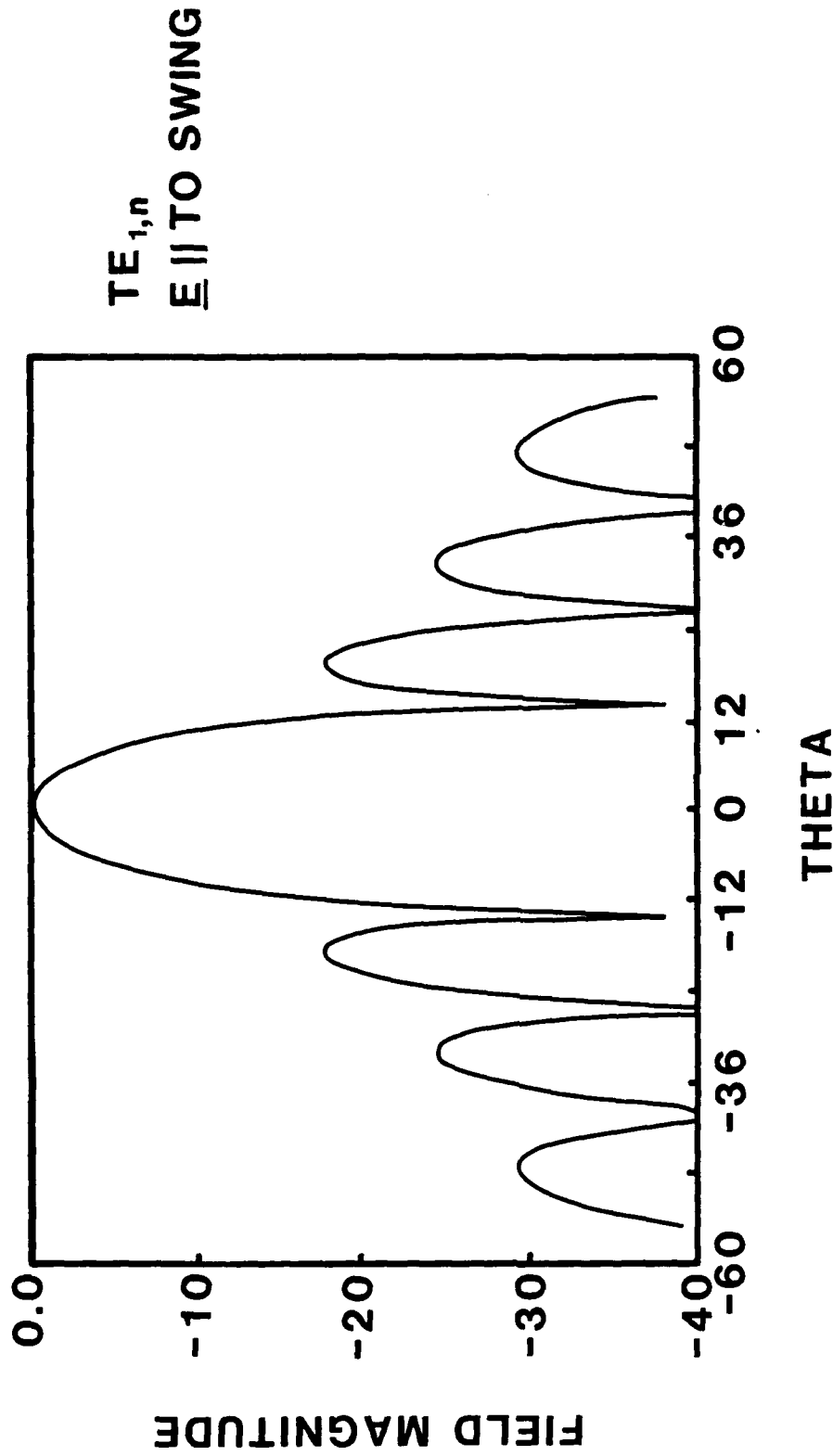
Figure 11: Theoretical far field mode pattern for $TE_{1,n}$ modes as a function of angle when the rectangular receiving horn is oriented vertically with respect to the direction of swing.

Far Field Pattern
94 GHz Gyrotron Oscillator
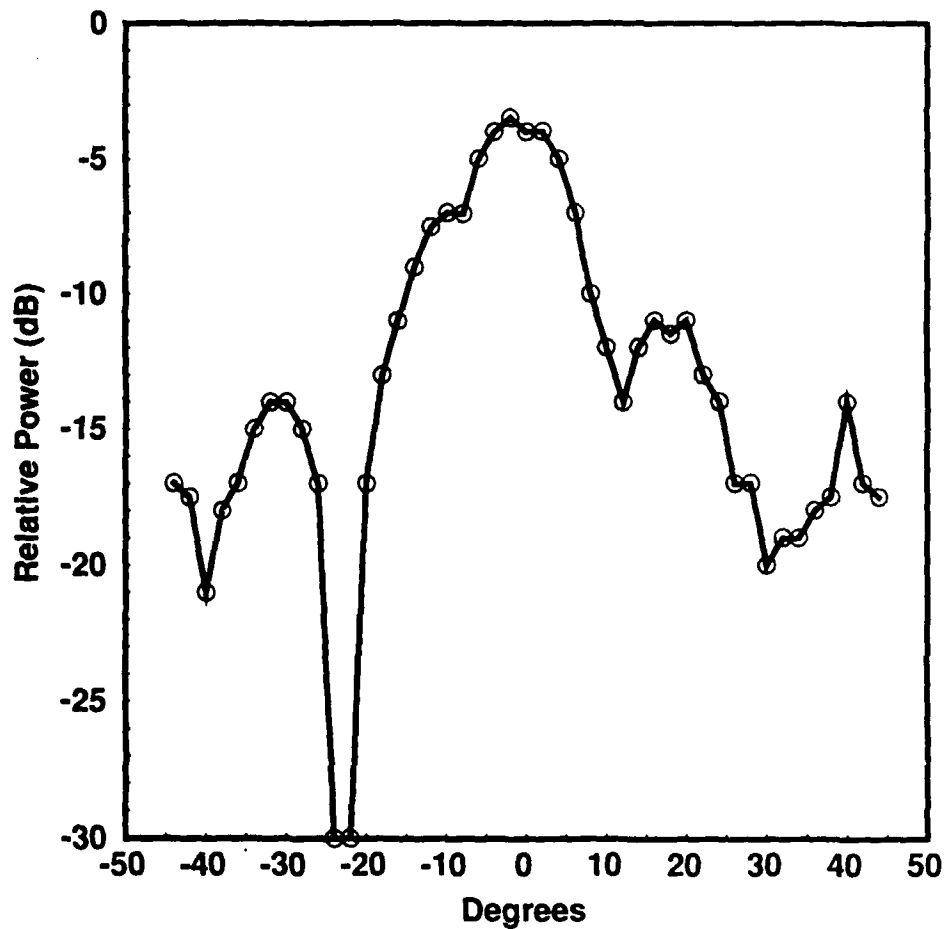
Horn orientation: vertical
Direction of sweep: horizontal   Measured frequency 94.3 GHz

Figure 12:   Measured far field mode pattern as a
function of horn angle. Each circle
represents a 2 degree increment from -45
degrees to +45 degrees.

THEORY – E PLANE
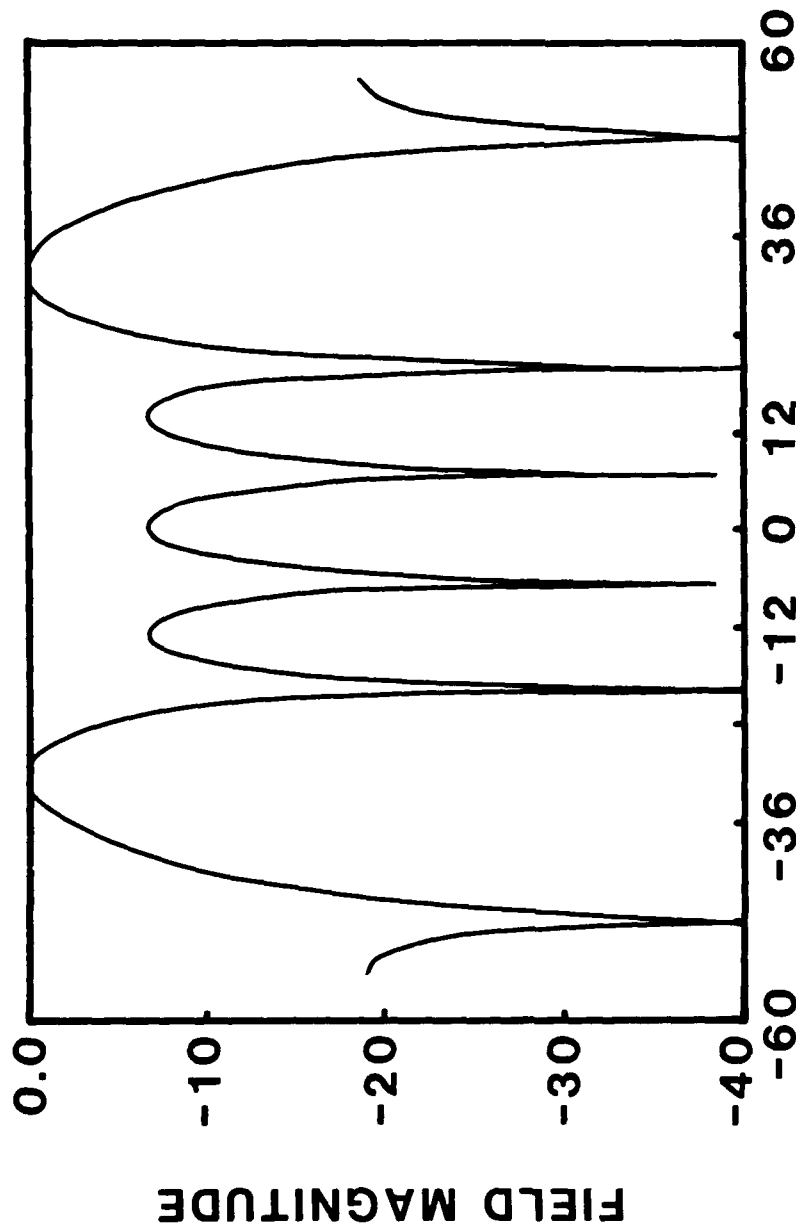
94 GHz
$TE_{1,3}$
HORN SWUNG $\perp$ to $\underline{E}$

FIELD MAGNITUDE

THETA

Figure 13: Theoretical far field mode pattern for $TE_{1,n}$ modes as a function of angle when the rectangular horn is oriented horizontally with respect to the direction of swing.

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Far Field Pattern
94 GHz Gyrotron Oscillator

Horn orientation: horizontal   Measured frequency 94.3 GHz
Direction of sweep: horizontal

Figure 14: Measured far field mode pattern as a function of horn angle. Each circle represents a 2 degree increment from -45 degrees to +45 degrees.
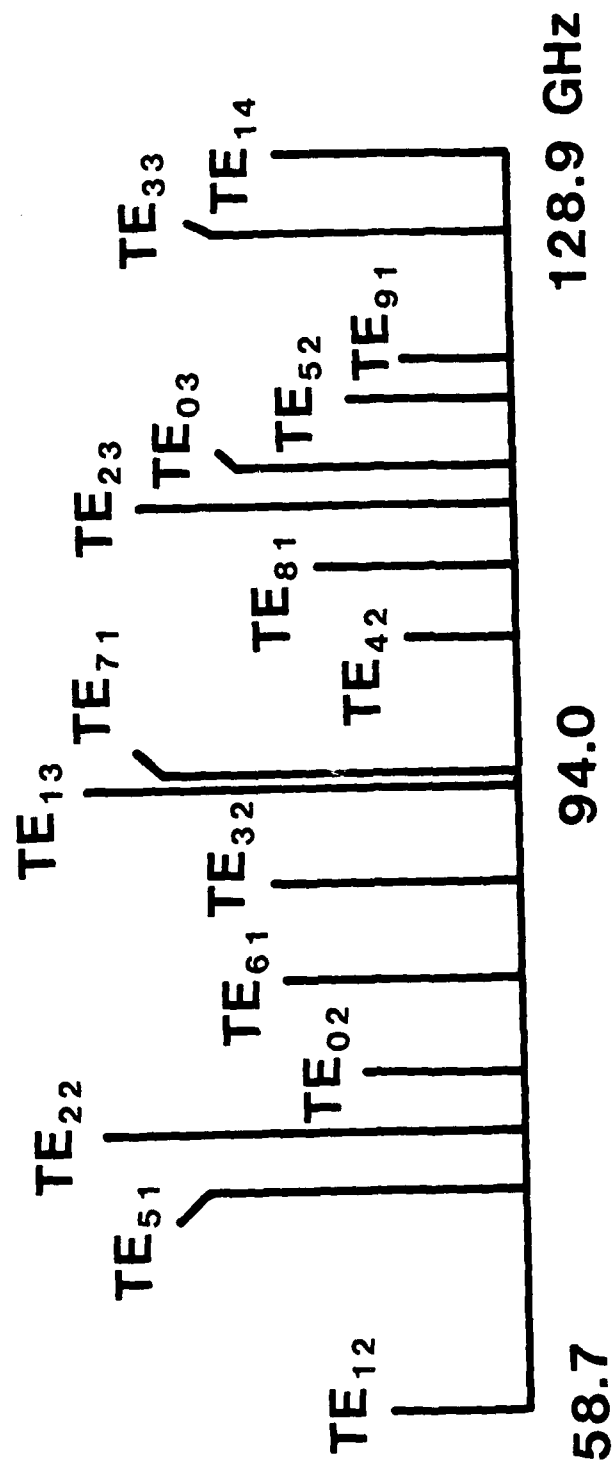
Figure 15: Map of the cutoff frequencies of TE_{mn} modes falling between 58.7 and 128.9 GHz for the unslotted TE_{13} cavity at 94 GHz.

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